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¹ Cambridge University Press.

² *Ann. Physik, Leipzig*, Ser. 4, 20, 237-68, 606-18 (1906); *Zs. physik. Chem., Leipzig*, 64, 686 (1908); 84, 410 (1913).

³ 18 papers in *J. Amer. Chem. Soc.*, 30, 33, 35.

⁴ *J. Amer. Chem. Soc.*, 33, 1060 (1911).

⁵ Richards and Coombs, *Ibid.*, 37, 1656-76 (1915); these PROCEEDINGS, 1, 404 (1915).

⁶ *Ann. Physik.*, Ser. 4, 9, 434 (1902).

OUTLINES OF A PROPOSED SYSTEM OF CLASSIFICATION OF THE NEBULAE BY MEANS OF THEIR SPECTRA*

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This paper may properly be considered a continuation of one previously published in these PROCEEDINGS, 1, 266 (1915). In that article the opinion is expressed that the behavior of the line 4686A might serve as the basis of a classification of the nebulae. The notion will be discussed here in greater detail. About eleven of the planetary nebulae have been studied with a fair degree of completeness, and while this number is too low to afford the most secure basis for broad generalizations, the observations seem to point the way to a rational system of classification of these objects on the basis of their spectra.

In figure 1 are reproduced the spectra of nine planetary nebulae and the great nebula in Orion. As stated in the earlier paper the method adopted for observing the spectra of such nebulae consists in placing the slit of the spectrograph directly across the image. In this way the length of a spectral line is made to furnish a measure of the extent of the occurrence of the emitting material in the nebula.

The first spectrum shown is that of N. G. C. 7027. This nebula consists of two nuclei, of unequal brightness, surrounded by fainter nebulosity. In photographing the spectrum the slit was placed in the line of the two nuclei. The spectrum shows the nebula to be unusually homogeneous. Some of the fainter lines appear to be short but that is probably merely the result of their faintness, as they are no shorter than the

*This and the following paper contains, in abbreviated form, the substance of one read before the eighteenth (Pacific Coast) meeting of the American Astronomical Society, under the title: *The spectra of the gaseous nebulae and some points of correspondence between them and other celestial spectra.*

strong lines appear with greatly reduced exposure. None of the lines exhibit any tendency to undue localization in the nuclei. The fourth strong line from the right is 4686A, whose origin has so engaged the attention of physicists in recent years. It is quite as long as lines of equal strength in other parts of the spectrum. Flanking this line on either side are groups of fainter lines which should be noted, as they play important parts in the discussion which is to follow.

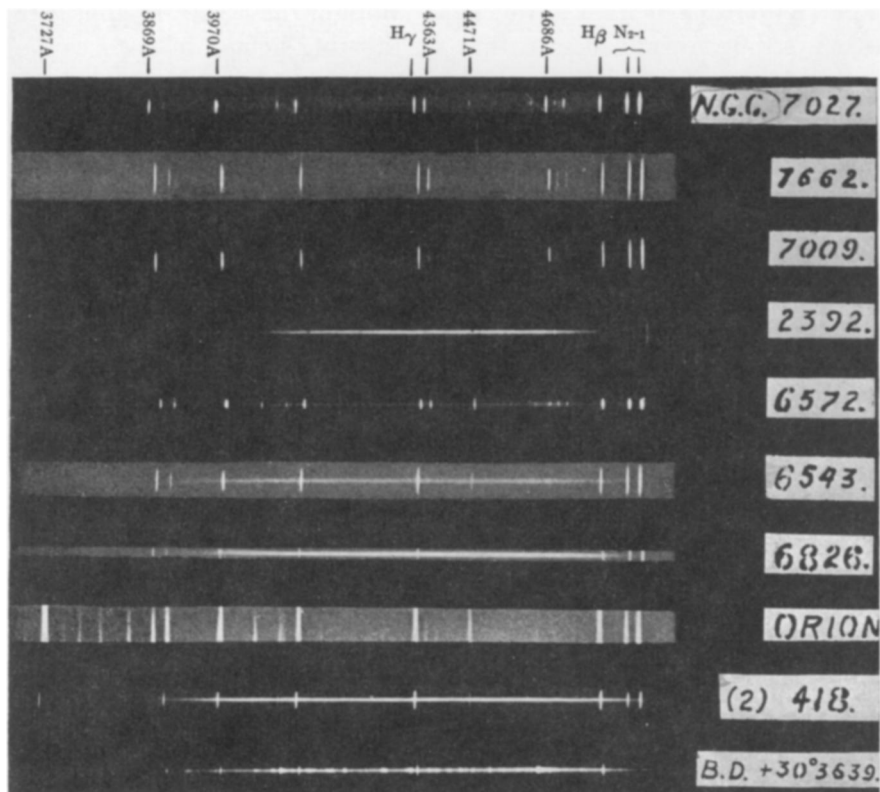


FIG. 1. SPECTRA OF NEBULAE.

The nebula N. G. C. 7662, whose spectrum follows, consists of a nucleus surrounded by an elliptical ring, the whole lying on a somewhat complicated background of fainter nebulosity. The increased brightness of most of the nebular lines where they cross the ring is plainly evident, particularly where the lines are not over-exposed. The line at wave-length 4686A and its neighbors are shorter than the others. They terminate sharply at the ring, and do not extend out into the faint outlying nebulosity and their brightness at contact with the ring itself is not greatly increased, which shows that they are relatively bright in

the comparatively dark area within. 4363A is longer than the members of this group but shorter than the hydrogen ($H\beta$, $H\gamma$, $H\delta$, $H\epsilon$) and nebulium (N_{2-1}) lines. Although the exposure extended over 17 hours the continuous spectrum of the nucleus is only faintly recorded, a fact which may be due, in part, to poor observing conditions.

Both in form and in spectrum the object N. G. C. 7009 bears a striking resemblance to 7662, and the purpose of exhibiting the spectrum is partly to call attention to this fact. Both of these spectra appear to bear a strong resemblance to that of the ring nebula in *Lyra* as described by Max Wolf, and it may be that in general objects of this form have a characteristic spectrum. The spectrum of the nucleus of N. G. C. 7009 is continuous, but the record is not strong enough to prove the presence or absence of dark lines.

N. G. C. 2392 is the nebula in *Gemini* which consists of two concentric rings of nebulosity surrounding a very bright nucleus. The usual nebular lines, including those due to hydrogen and helium, are present in the outlying nebulosity, but in the nucleus the hydrogen and helium lines are reversed, that is, they appear as dark lines. 4686A on the contrary is brightened and probably broadened on crossing the spectrum of the nucleus. One might expect, from this apparent tendency of the line to concentrate in the nucleus, to find it comparatively short in the nebula, but as a matter of fact it appears to be quite as long, in this object, as any of the other lines. In fixing the position of the spectrum in an order, the controlling factor of whose arrangement is the degree of concentration of the line 4686A, there is therefore some doubt as to which of these phenomena should control. As a nebular line the one in question is relatively longer in this nebula than in N. G. C. 7662, which should place it before that object, while its increased breadth in the nucleus would seem to indicate a position intermediate between N. G. C. 7009 and 6572. In the dilemma I have tentatively assigned it to the latter position. In addition to the dark lines referred to above, the ζ *Puppis* series is also dark in the spectrum of the nucleus.

The nebula N. G. C. 6572, or Struve 6, is a small object which brightens gradually to a hazy nucleus near the center. It will be noticed that the line 4686A is confined to the nucleus, and that it has completely lost its monochromatic character. It has the appearance of a hazy ball. The lines flanking it on either side are very short, and some of them are broadened. The lines of these groups become very active in the *novae* and some of them play important rôles in the Wolf-Rayet (Class O) spectra. The well-known lines 4634 and 4650A are among them. The spectrum of this nucleus has several of the characteristic

Wolf-Rayet bands, in addition to that at 4686A. One of these shows very faintly at 4057A. While the nucleus is undoubtedly to be considered a Class O star, I am in some doubt as to its exact position in the Harvard scale.

The spectrum of N. G. C. 6543 very much resembles the one immediately above it, except that the nebulous envelope is comparatively much larger. Five of the critical lines in the vicinity of 4686A are very short, while two of them: 4641 and 4713 are of medium length. The nucleus band, 4057A, visible only with difficulty in N. G. C. 6572, is strongly developed here. Unlike the one at 4686A, this band does not appear to have its counterpart in a true nebular spectrum, that is, it has not been observed except as a broad band confined to nebular nuclei, or other Class O stars. As in most of the other spectra the lines are of various lengths, helium being intermediate in extent between 4686A and hydrogen. The other lines fall in their usual order of length.

The following subject is the spectrum of the central region of N. G. C. 6826. The spectrum of the nucleus resembles that of the preceding object, but has the additional feature of interest that the nucleus band at 4686A, and probably the bright hydrogen lines, are accompanied on their more refrangible edges by dark lines in the spectrum of the nucleus. Dark ζ *Puppis* lines are also present, though faint, and H and K (Calcium) are also dark. In addition to 4686A, 4658 and perhaps 4650 occur as bright bands in the nucleus.

As has already been remarked, the nebula N. G. C. Index 418, situated in the southern part of the constellation of Orion, was found by Campbell to have a hydrogen atmosphere of greater extent than that of its 'nebular' atmosphere. The photograph confirms this result, and shows in addition the restricted occurrence of helium. The details of the nucleus spectrum are lost on this plate, through overexposure, so that it is necessary to state that 4650 and 4686A are present as broadened bands confined to the nucleus, the first named line being much the stronger. In the downward progression this line has developed from a comparatively insignificant nebular line into the strongest band in the spectrum of the nucleus.

The spectrum immediately below is that of the well-known Wolf-Rayet star B.D. +30°3639 which Campbell found to be surrounded by a hydrogen atmosphere. As announced a year ago it is in reality a planetary nebula with a highly complicated nucleus. The line 4686A and most of the neighboring lines which occur as nebular lines in N. G. C. 7027 are here represented by broad bands in the nucleus. Helium is in the nucleus, while hydrogen is still outstanding in the nebula.

The nebula N. G. C. 40, the spectrum of which is shown in figure 2, is a large dim ring with a comparatively bright nucleus. The spectrum was photographed with a very short camera, so the scale is small. The nebular spectrum is shown to consist principally of the hydrogen lines and the ultra-violet line at 3727Å. As is usual in such cases the lines show knots at their extremities corresponding to the bright edges of the ring. N_1 and N_2 are present, though they are exceedingly faint, and appear to be short. The spectrum of the nucleus is over-exposed on this plate and is shown to better advantage, with reduced exposure, in figure 3. The original negatives of this spectrum are very small and the necessary enlargement has been so great that the definition is not of the best. It will be seen, however, that the spectrum of the nucleus is made up of numerous hazy bright bands, and measurement proves these to be well-known Wolf-Rayet radiations. There are seventeen of them in addition to the hydrogen bands. The brightest is 4650Å, and the lesser one beside it is 4686Å. If it is true that the nebulae

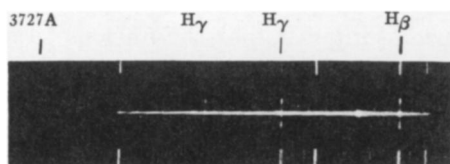


FIG. 2. SPECTRUM OF N.G.C. 40.

FIG. 3. SPECTRUM OF NUCLEUS
N.G.C. 40.

are condensing into stars there are reasons for supposing that this one is further along in the process than any of the others we have studied.

In presenting these spectra an endeavor has been made to arrange them according to the degree of concentration of 4686Å and some of the neighboring lines. It will be seen that the successive objects stand in very close relation to one another, yet at one end of the scale is a purely gaseous nebula, and at the other a banded star with only the shreds of nebulosity clinging to it.

Quite aside from any bearing which these observations may have on the subject of nebular evolution it appears to me that they offer the basis for a satisfactory classification of the nebulae. The observation of many of the nebulae for the purpose of investigating the degree of concentration of the lines which have been discussed would be impracticable but this, I believe, would hardly be necessary, for it will be observed that, having arranged the spectra in the order shown, there are certain progressions in the relative intensities of some of the comparatively bright lines which would serve to fix the positions of any of the spectra in the adopted scale. For instance, consider the doublet

at 3970A. The component to the right is H_{ϵ} , the one to the left is of unknown origin. These lines are so close that they are only incompletely resolved on some of the plates, a rough estimate of their relative intensities may, however, readily be made, and it will be seen that in the upper spectrum the left hand component is much the stronger. As we go down the line it loses steadily in strength until in N. G. C. 6543 and 6826 the two components are equal. In the Orion nebula, which has been inserted here, the left hand member is much the weaker of the two, while in the last two objects this component is practically missing. The same may be said of 3869A; it is strong in the upper pictures and finally fades out in the descent. In what appears to be a lesser degree there is a corresponding variation of the lines N_{1-2} ; that is, the so-called chief nebular lines gradually weaken with reference to those of hydrogen. The line 3727A, on the other hand, undoubtedly strengthens in the downward progression, though this does not show very clearly in these plates by reason of the fact that the 36-inch refractor is an unsuitable instrument for studying the ultra-violet, the region of the spectrum in which these lines lie. The spectrum of the Orion nebula, in which this line shows so prominently, was made with the 12-inch telescope; aside from the undue strength of 3727A, which is to be accounted for by this fact, this spectrum is found to correspond closely with those on either side of it, and appears to be intermediate between them. There is therefore no essential difference between it and the spectra of the planetary nebulae which may be said to belong to the same class.

In the course of this work the spectra of nine planetary nebular nuclei have been examined. In two cases the observations so far made are not competent to determine with certainty the nature of the spectra. The remaining seven are undoubtedly Class O stars. I think it a fair inference that the nebulae and the Class O stars in general stand next to each other in the course of stellar evolution. If, as some astronomers believe, certain of the red stars stand next to the nebulae, it is remarkable that we do not find them associated with these objects. All of the nebular nuclei stand high on the temperature scale, if we may judge from their great photographic, as compared with their visual, brightness. So far as the development of stars from gaseous nebulae may be concerned the evidence seems to favor the usually accepted theory, rather than the red to red progression favored by Lockyer and some others: